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(54) **APPARATUS FOR FLEXIBLE ELECTRONIC INTERFACES AND ASSOCIATED METHODS**

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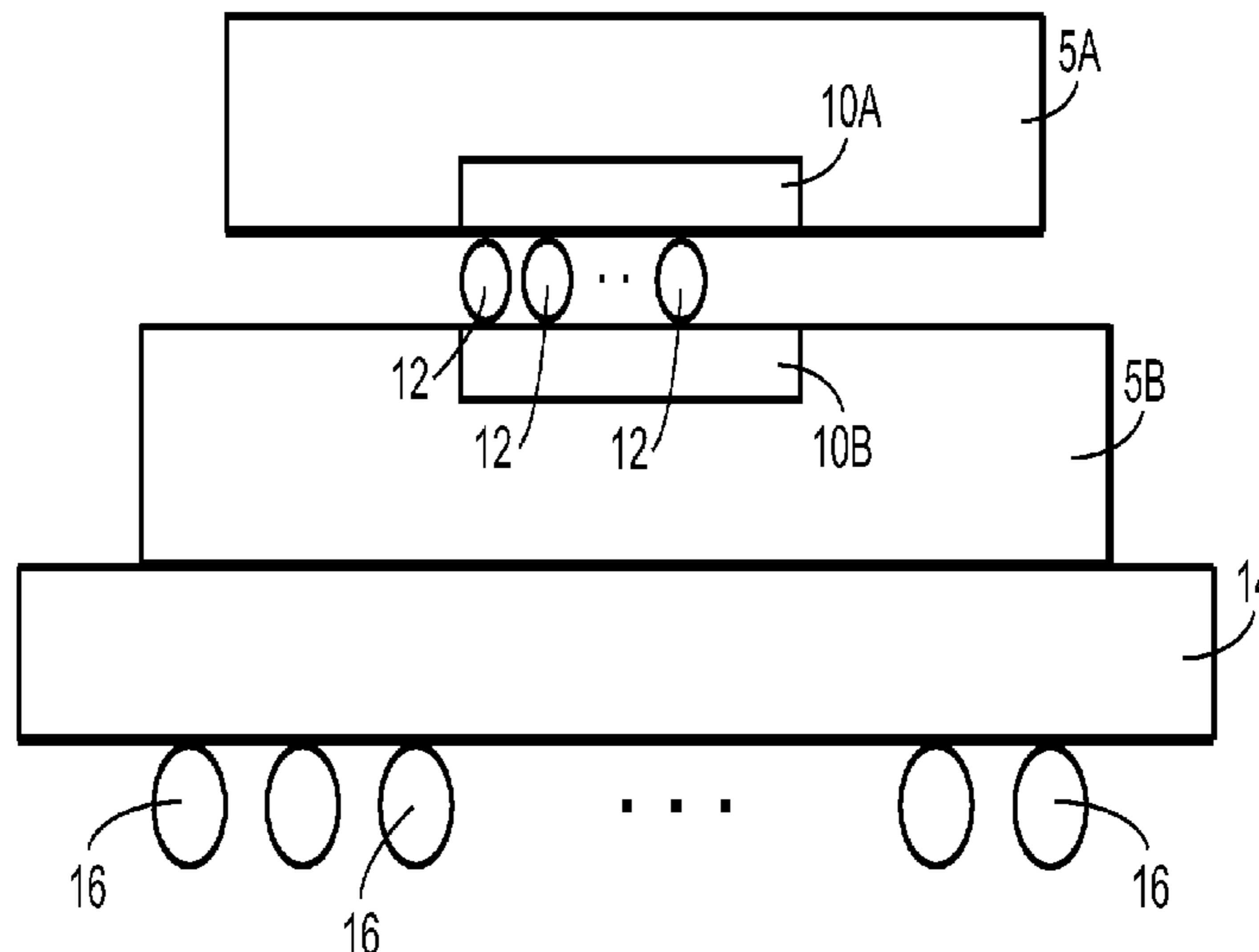
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(57) **ABSTRACT**

A semiconductor die includes at least one flexible interface block. The flexible interface block includes at least one interconnect, and at least one buffer coupled to the at least one interconnect. The flexible interface block further includes a routing interface coupled to circuitry integrated in the semiconductor die, and a controller coupled to provide communication between the routing interface and the at least one buffer.

**20 Claims, 13 Drawing Sheets**



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- (52) **U.S. Cl.**  
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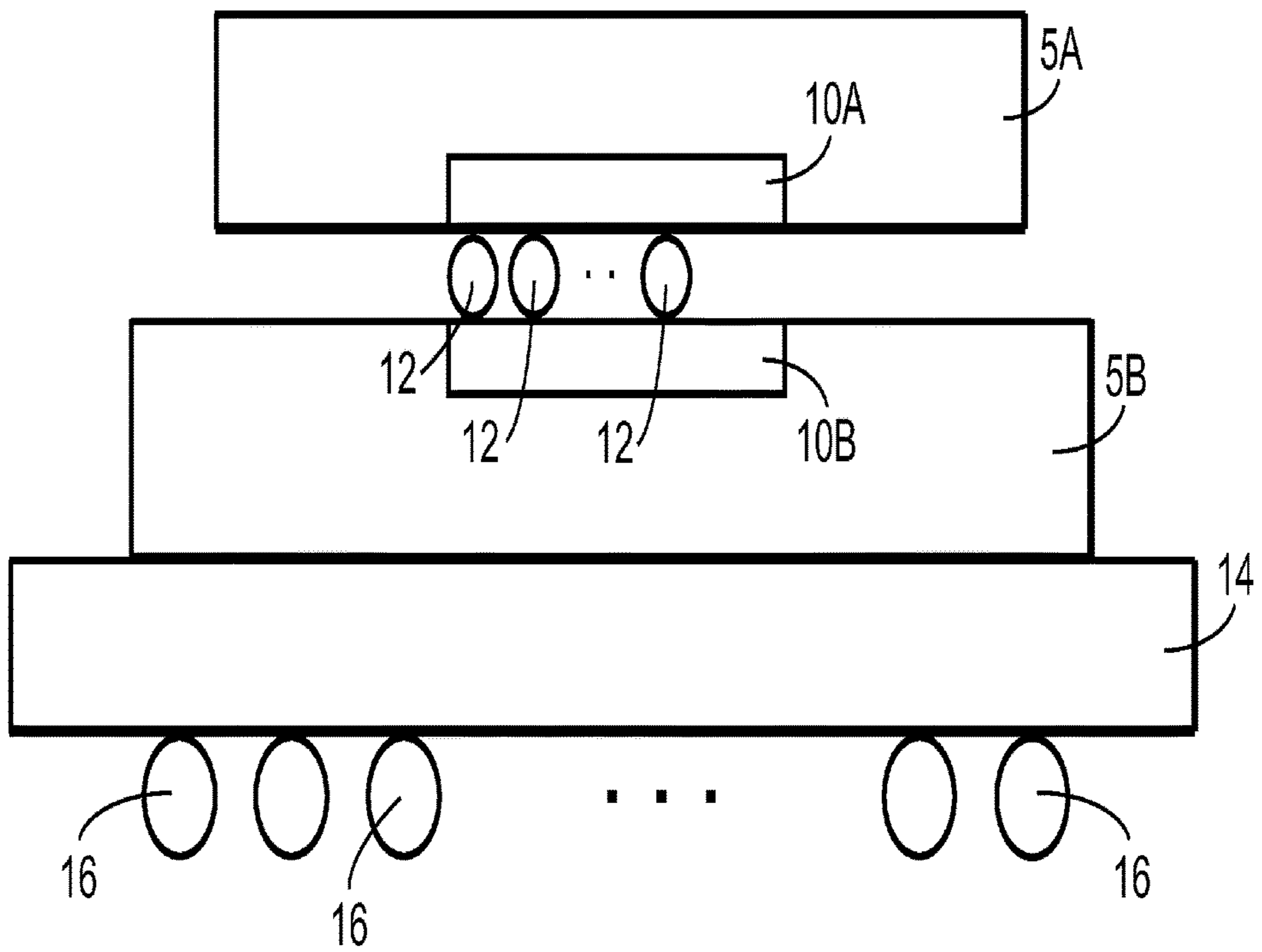


Fig. 1

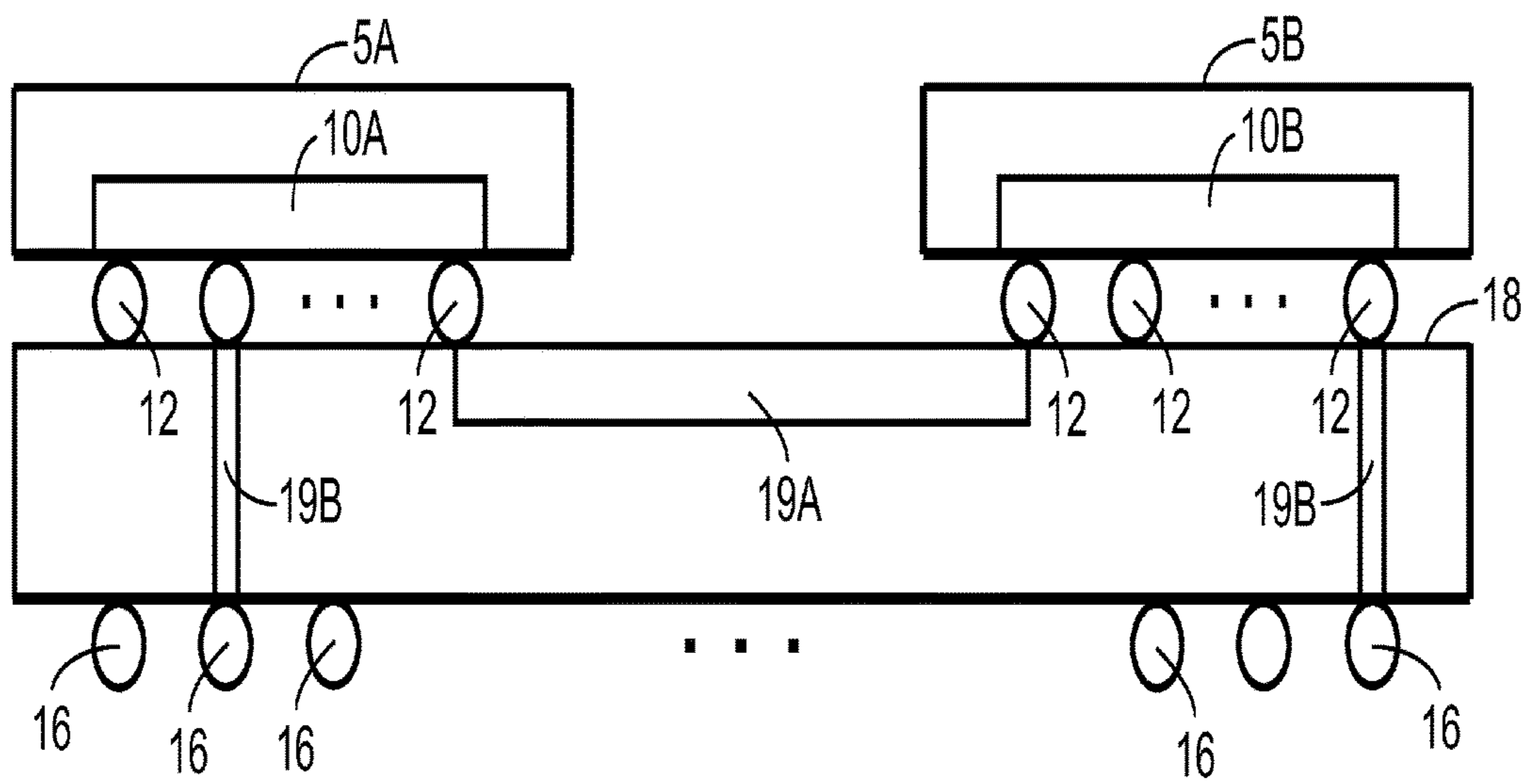


Fig. 2

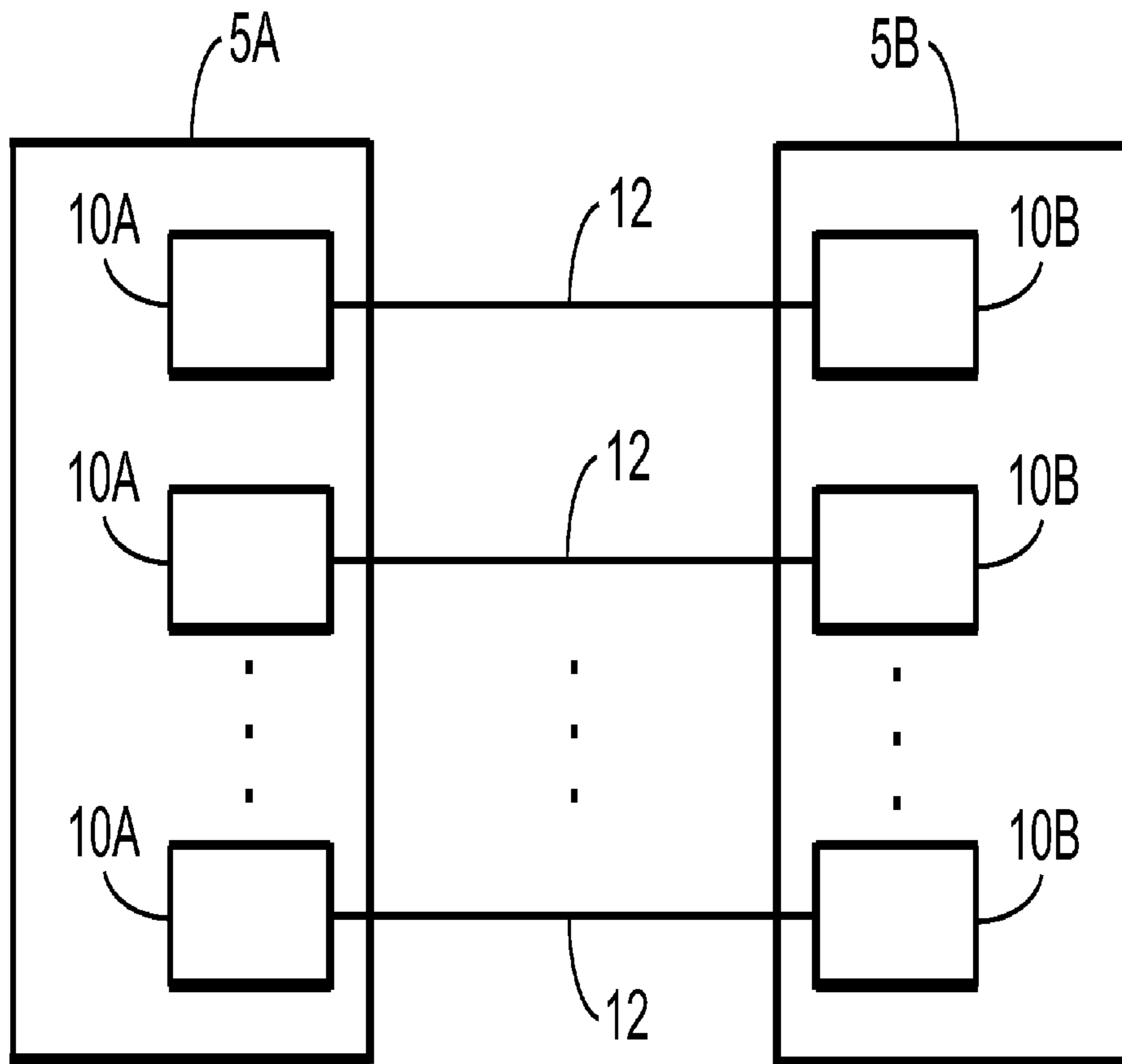


Fig. 3

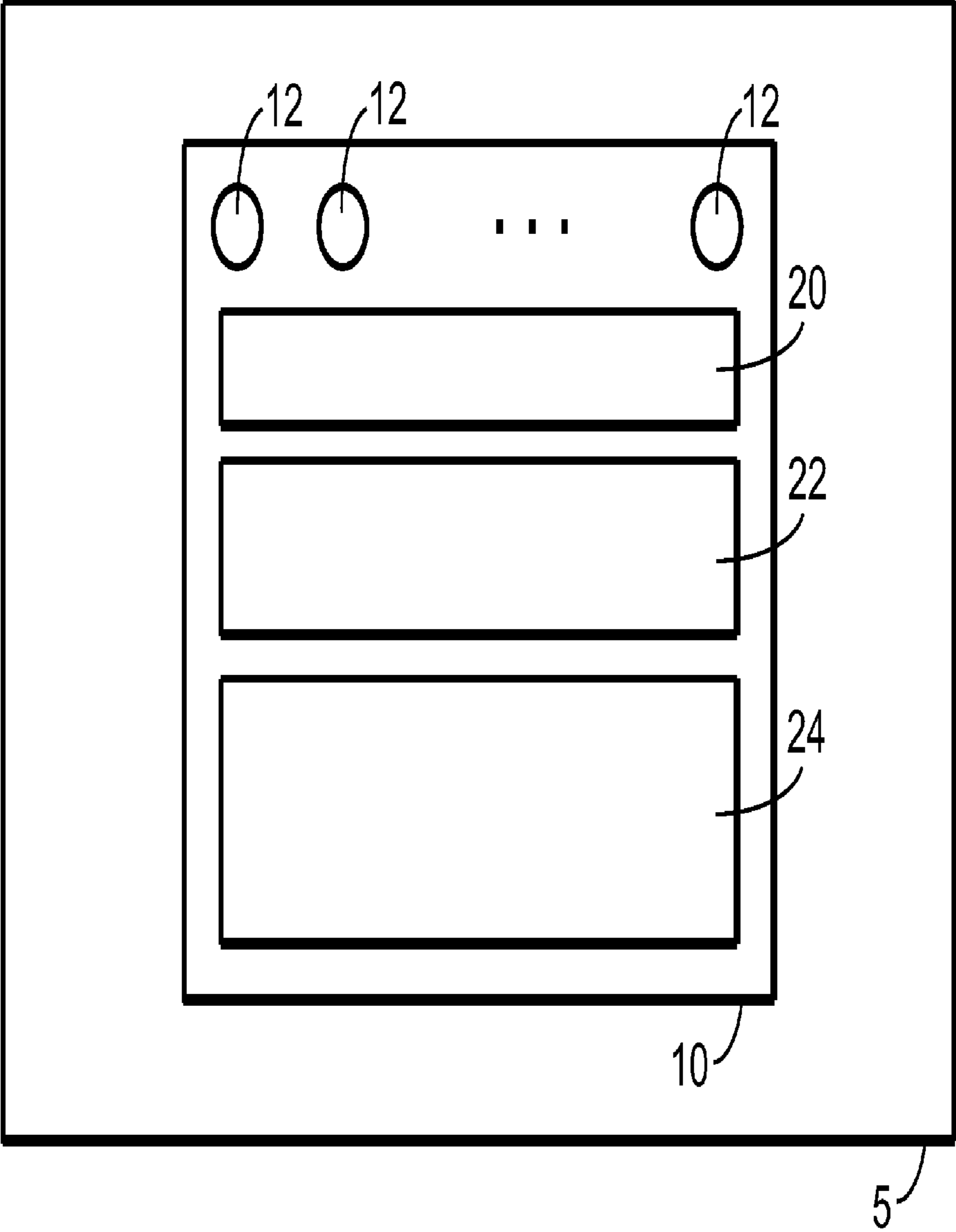


Fig. 4

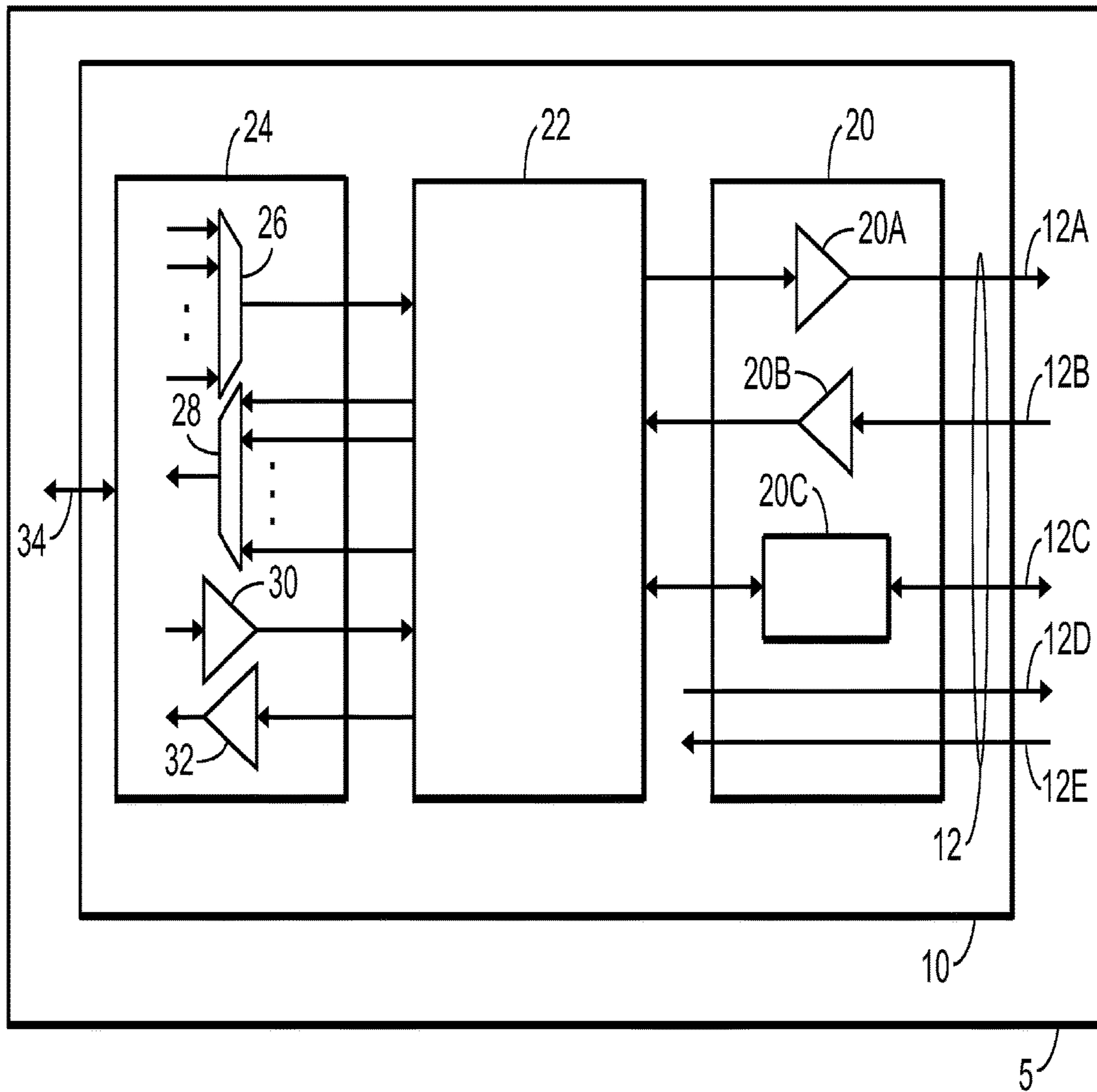


Fig. 5

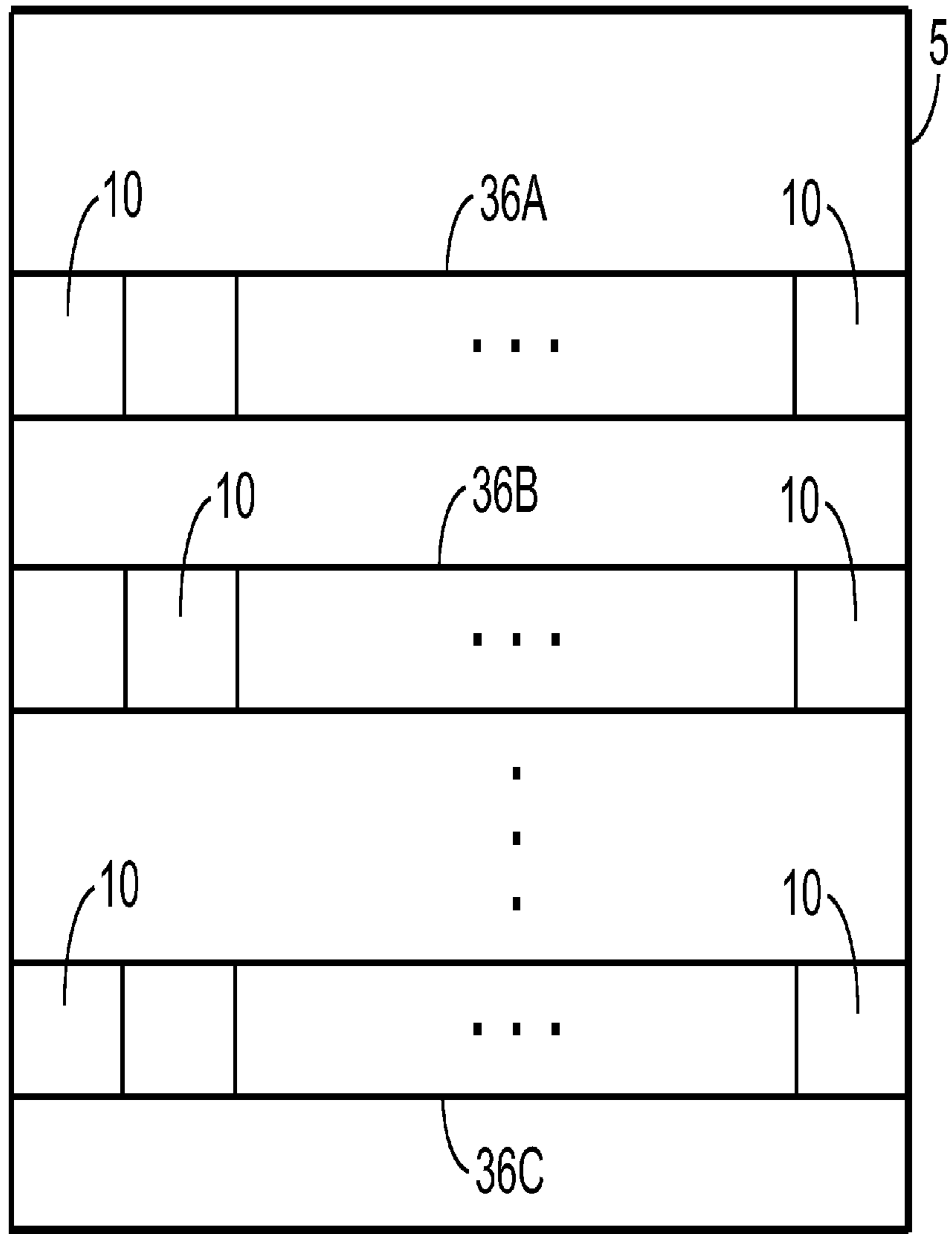


Fig. 6



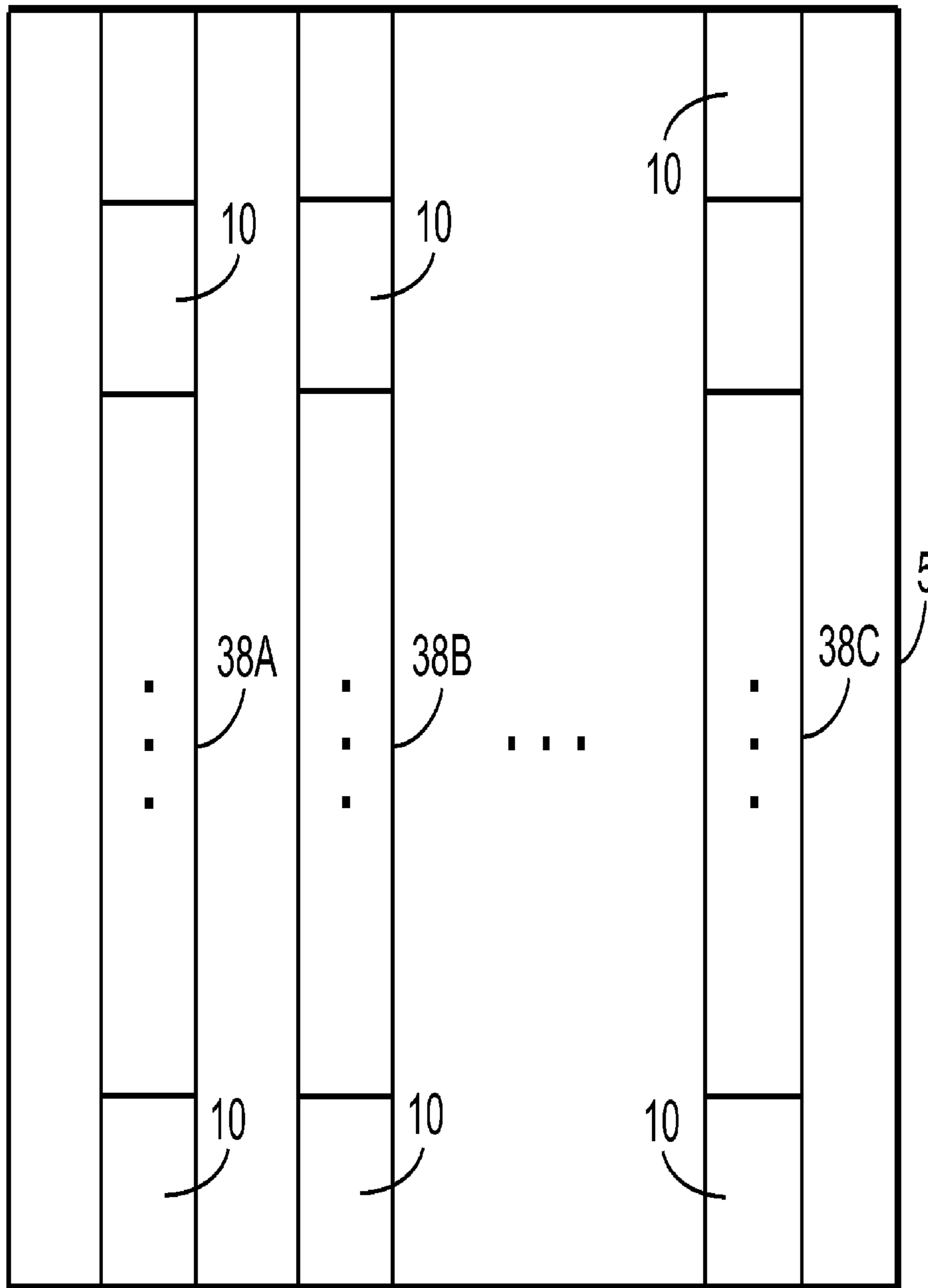


Fig. 7

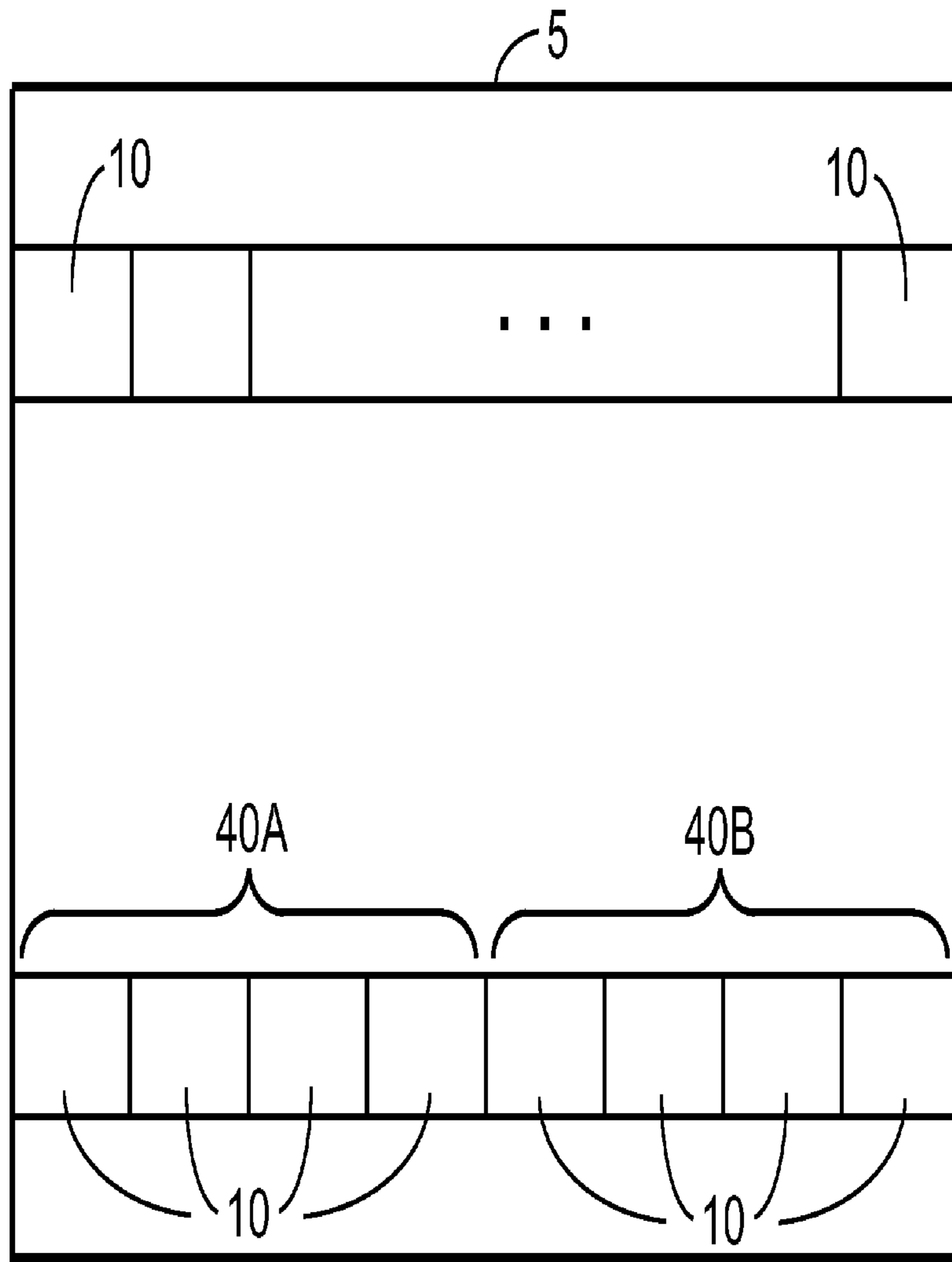


Fig. 8

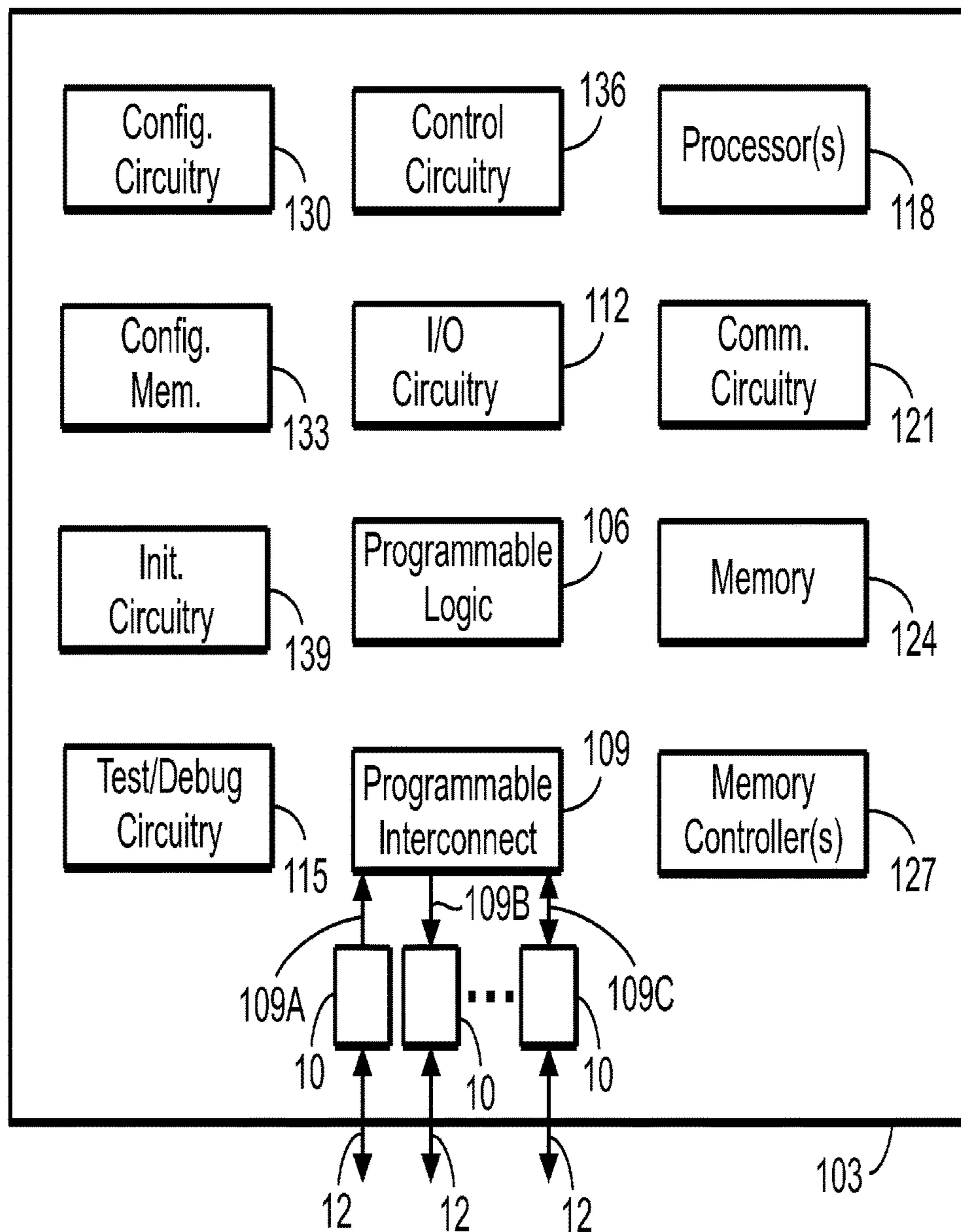


Fig. 9

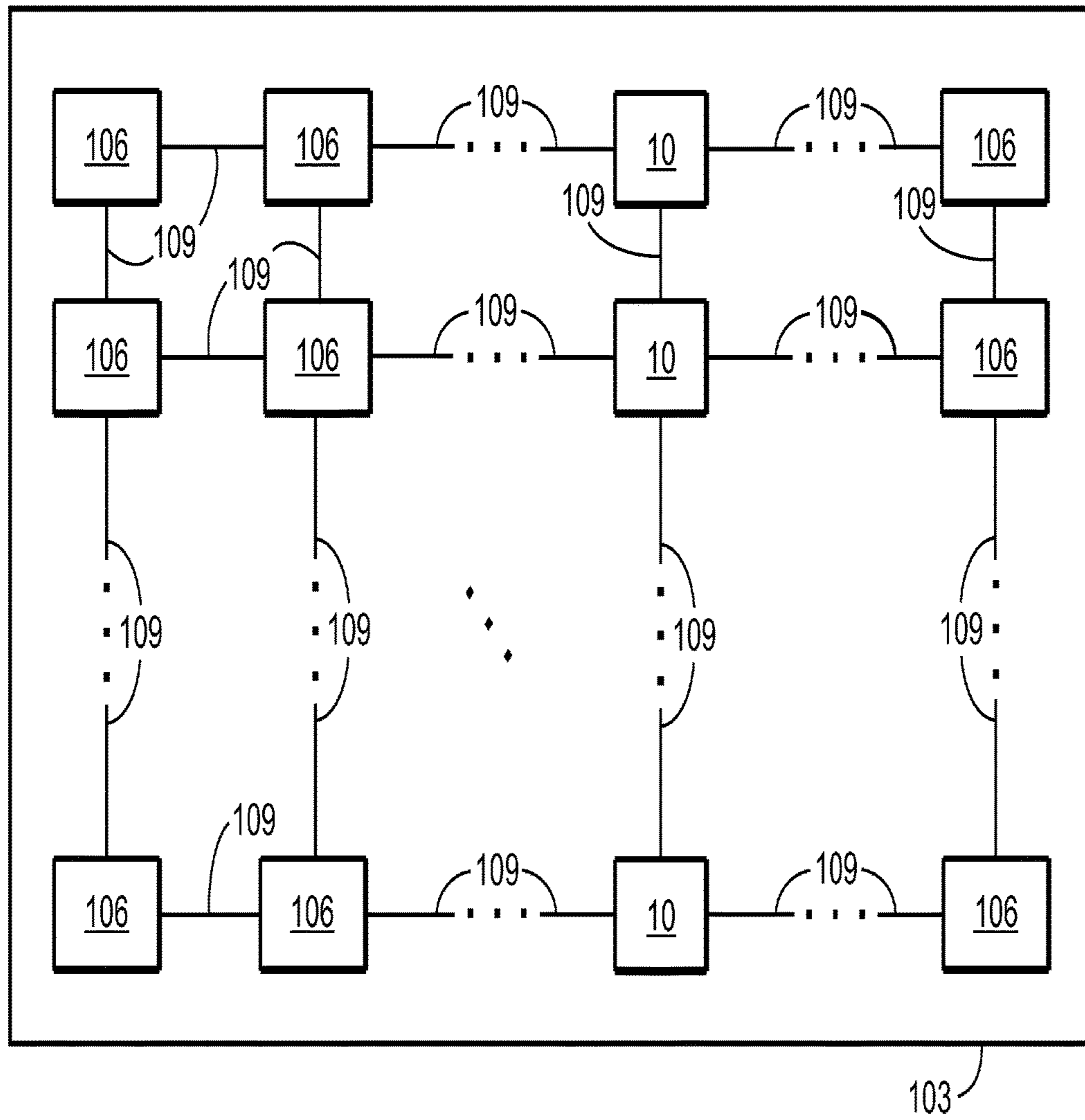


Fig. 10

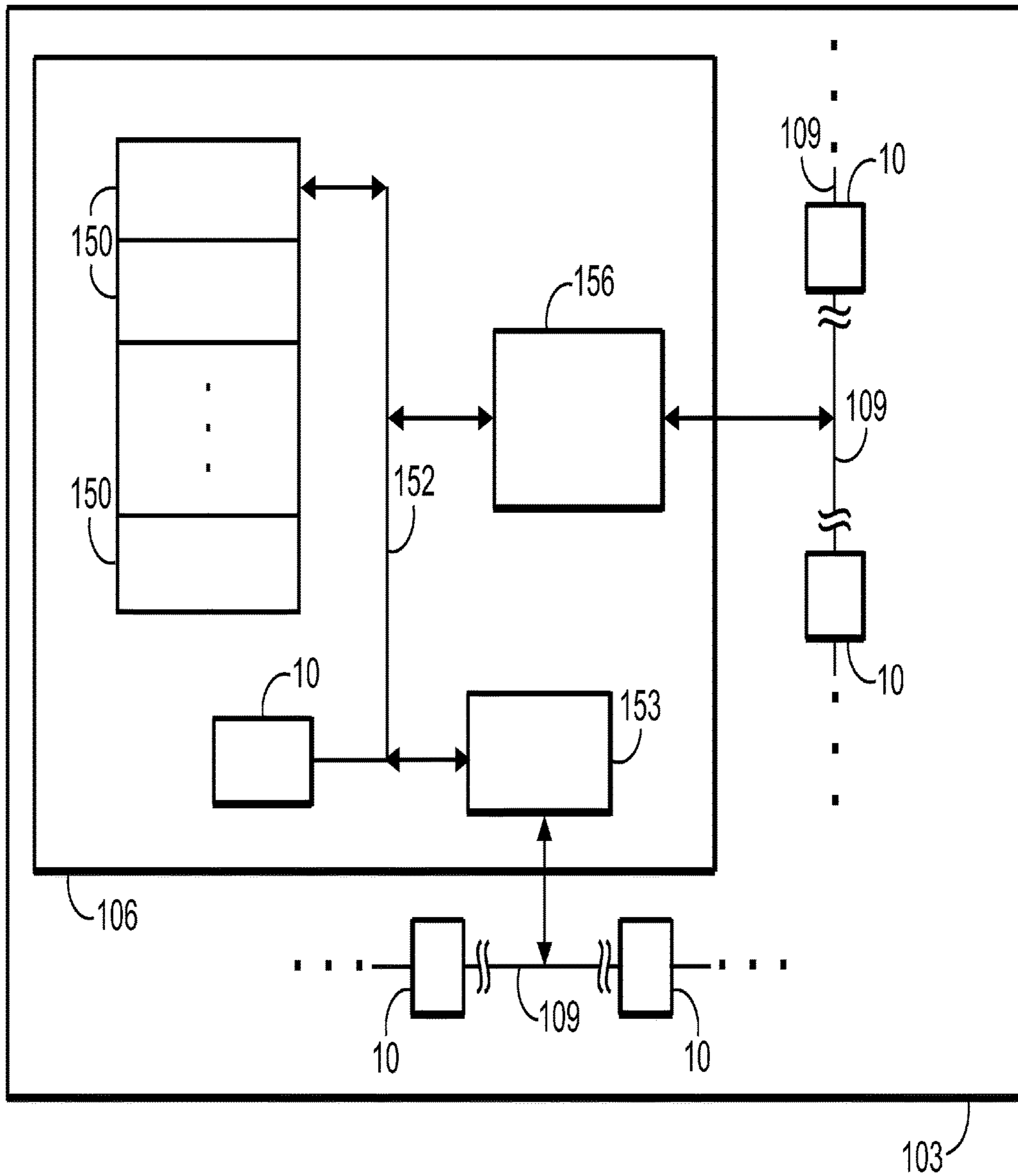


Fig. 11

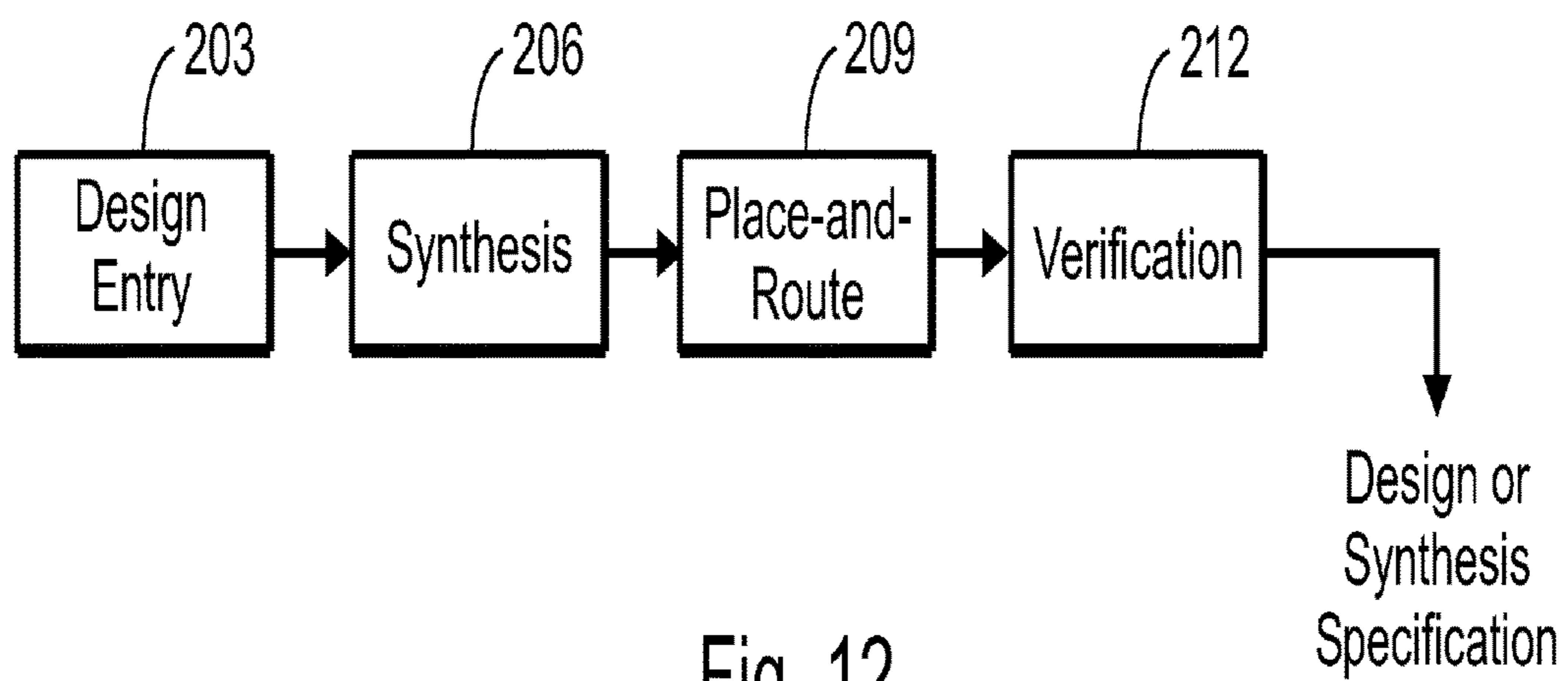


Fig. 12

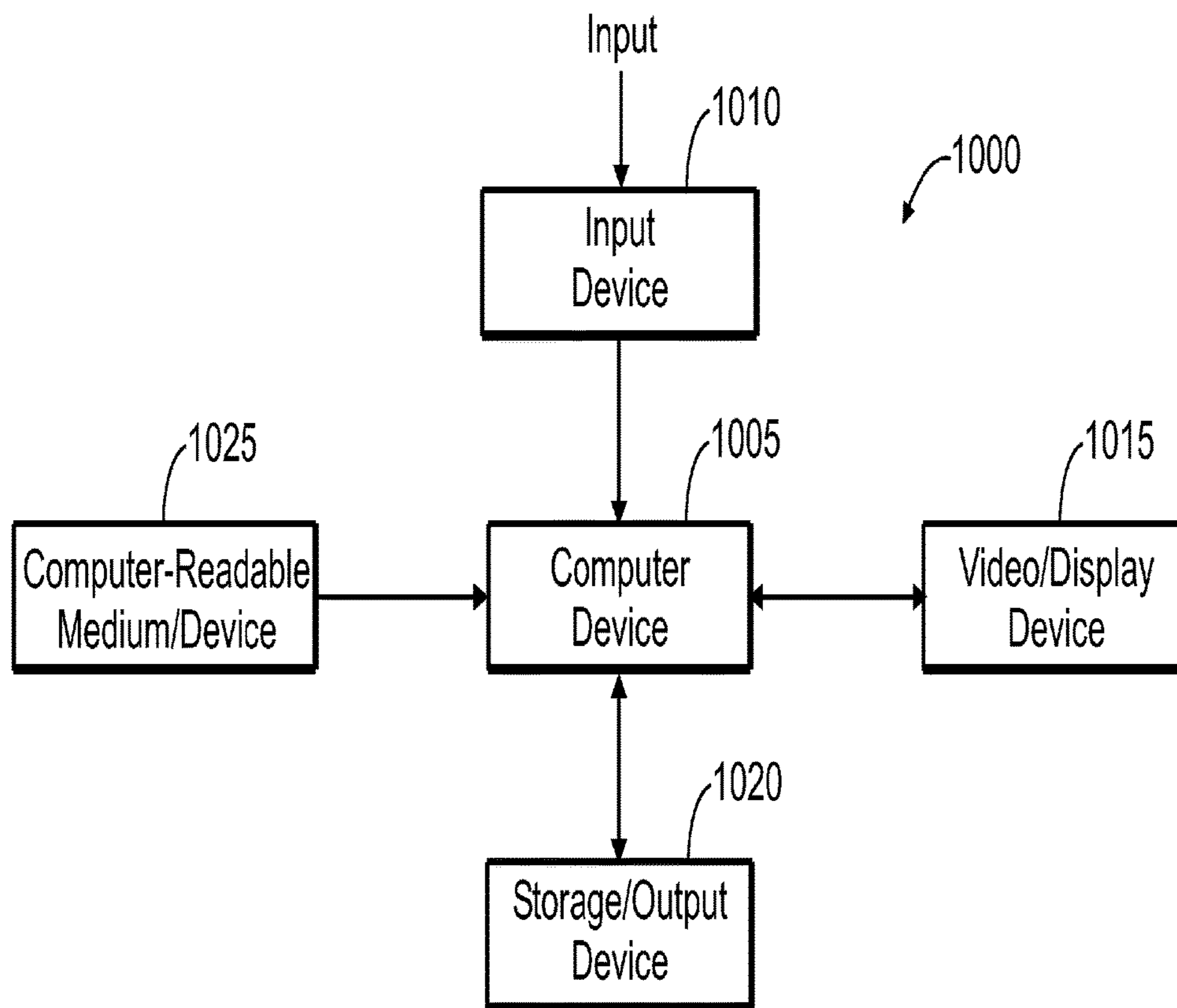


Fig. 13

## APPARATUS FOR FLEXIBLE ELECTRONIC INTERFACES AND ASSOCIATED METHODS

This application is a continuation of U.S. patent application Ser. No. 13/350,662, filed on Jan. 13, 2012, which is hereby incorporated by reference herein in its entirety. This application claims the benefit of and claims priority to U.S. patent application Ser. No. 13/350,662, filed Jan. 13, 2012.

### TECHNICAL FIELD

The disclosed concepts relate generally to electronic circuitry and, more particularly, to apparatus for flexible or universal electronic interface circuitry, and associated methods.

### BACKGROUND

Advances in electronics has allowed increased levels of integration. The technology for fabrication of ICs has contributed to those advances, and has provided a vehicle for integrating a relatively large number of circuits and functions into an IC. As a result, present-day ICs might contain hundreds of millions of transistors. Notwithstanding the large number of transistors, the desired functionality of an electronic device or circuit sometimes entails using the circuitry of more than one IC. To facilitate the implementation of such functionality, sometimes two or more semiconductor die are used and coupled to one another.

### SUMMARY

A wide variety of embodiments according to the disclosed concepts may be used to provide apparatus and methods for flexible electronic interfaces. In one exemplary embodiment, a semiconductor die includes one or more flexible interface blocks. The flexible interface block includes at least one interconnect, at least one buffer, a routing interface, and a controller. The at least one buffer is coupled to the at least one interconnect. The routing interface is coupled to circuitry integrated in the semiconductor die. The controller is coupled so as to provide communication between the routing interface and the at least one buffer.

In another exemplary embodiment, an apparatus includes a first semiconductor die that includes a first interface circuit and a first circuit coupled to the first interface circuit. The apparatus also includes a second semiconductor die, including a second circuit, where the second semiconductor die is coupled to the first interface circuit. The first interface circuit provides a customizable interface between the first and second circuits.

In yet another exemplary embodiment, a method is provided for modeling an implementation of an electronic design using a programmable logic device (PLD) integrated in a first semiconductor die and using a circuit integrated in a second semiconductor die. The method is implemented using a computer. The method includes modeling the implementation, using the computer, by representing the circuit as a flexible interface block of the PLD coupled to the circuit.

### BRIEF DESCRIPTION OF THE DRAWINGS

The appended drawings illustrate only exemplary embodiments and therefore should not be considered as limiting its scope. Persons of ordinary skill in the art appreciate that the disclosed concepts lend themselves to other equally effective embodiments. In the drawings, the

same numeral designators used in more than one drawing denote the same, similar, or equivalent functionality, components, or blocks.

FIG. 1 illustrates an arrangement of semiconductor die that use flexible interface circuitry according to an exemplary embodiment.

FIG. 2 depicts an arrangement of semiconductor die that use flexible interface circuitry according to another exemplary embodiment.

FIG. 3 shows a circuit arrangement according to an exemplary embodiment for coupling together circuitry in semiconductor die by using one or more flexible interface blocks.

FIG. 4 depicts a block diagram of a flexible interface block according to an exemplary embodiment.

FIG. 5 illustrates more details of a flexible interface block according to an exemplary embodiment.

FIG. 6 depicts an arrangement of flexible interface blocks in a semiconductor die according to an exemplary embodiment.

FIG. 7 illustrates an arrangement of flexible interface blocks in a semiconductor die according to another exemplary embodiment.

FIG. 8 shows grouping of flexible interface blocks in a semiconductor die according to an exemplary embodiment.

FIG. 9 illustrates a general block diagram of a programmable logic device (PLD) that includes one or more flexible interface blocks.

FIG. 10 depicts a block diagram of a PLD that includes programmable resources and flexible interface blocks according to an exemplary embodiment.

FIG. 11 shows a block diagram of a PLD that includes programmable resources and flexible interface blocks according to another exemplary embodiment.

FIG. 12 illustrates a block diagram of various modules of a PLD computer-aided design (CAD) software or flow according to an exemplary embodiment.

FIG. 13 depicts a block diagram of a system for processing information, such as a CAD flow, according to an exemplary embodiment.

### DETAILED DESCRIPTION

The disclosed concepts provide apparatus and related techniques for flexible (or universal) electronic interface circuitry. More specifically, the flexible interface circuitry provides a mechanism for coupling two or more semiconductor die. The flexible interface circuitry can be used in a variety of configurations, and can provide efficient and fast interfaces between semiconductor die.

In some instances, two or more semiconductor die are arranged vertically. For example, one semiconductor die may be positioned or stacked above another semiconductor die. Additional semiconductor die may be positioned or stacked above this structure. As described below in detail, the flexible interface circuitry may be used to couple together two or more of the semiconductor die.

FIG. 1 illustrates an arrangement of semiconductor die that use flexible interface circuitry according to an exemplary embodiment. The exemplary arrangement shown includes two semiconductor die, labeled 5A and 5B, stacked or positioned above a substrate or base 14. Rather than two semiconductor die, other numbers of semiconductor die may be used and stacked vertically, as persons of ordinary skill in the art understand. Interconnect 16 (e.g., solder balls or bumps) provide a way for substrate 14 to couple to another medium, such as a printed circuit board (not shown).



Die **5A** includes at least one flexible interface circuit or block **10A**. Flexible interface block **10A** couples to circuitry integrated in die **5A**. The circuitry in die **5A** may have a variety of forms and provide a variety of desired or specified functionality. For example, the circuitry in die **5A** may include digital circuitry (gates, latches, flip-flops, registers, finite state machines, etc.), analog circuitry (amplifiers, adders, current and voltage sources, etc.), mixed-signal circuitry (analog to digital converters (ADCs), digital to analog converters (DACs), etc.), and/or discrete components (transistors, resistors, capacitors, inductors).

Similarly, die **5B** includes at least one flexible interface circuit or block **10B**. The circuitry in die **5B** may have a variety of forms and provide a variety of desired or specified functionality. For example, the circuitry in die **5B** may include digital circuitry (gates, latches, flip-flops, registers, finite state machines, etc.), analog circuitry (amplifiers, adders, current and voltage sources, etc.), mixed-signal circuitry (analog to digital converters (ADCs), digital to analog converters (DACs), etc.), and/or discrete components (transistors, resistors, capacitors, inductors).

Flexible interface block **10A** couples to flexible interface block **10B** via coupling mechanism or interconnect **12** (e.g., solder bumps, solder balls, microbumps, etc.). Interconnect **12** may include signal and power lines, as desired. In addition to providing an electrical coupling mechanism between die **5A** and die **5B**, interconnect **12** also provides a physical coupling between die **5A** and die **5B**. In other words, either alone or in conjunction with other structures (not shown), interconnect **12** provide physical support for die **5A**.

As noted above, flexible interface block **10A** couples to circuitry integrated in die **5A**, and flexible interface block **10B** couples to circuitry integrated in die **5B**. Because flexible interface block **10A** couples to flexible interface block **10B**, flexible interface blocks **10A-10B** provide a mechanism for coupling circuitry integrated in die **5A** to circuitry integrated in die **5B**.

As persons of ordinary skill in the art understand, the arrangement shown in FIG. **1** illustrates merely one embodiment, and a wide variety of other embodiments are possible and contemplated. Examples include three-dimensional (3D), 2.5D, face-to-face die bonding, face-to-back die bonding, die bonding using through silicon vias (TSVs) in one or more die, etc.

FIG. **2** depicts an arrangement of semiconductor die that use flexible interface circuitry according to another exemplary embodiment. Similar to the arrangement in FIG. **1**, the semiconductor die arrangement of FIG. **2** includes die **5A-5B**, flexible interface blocks **10A-10B**, interconnect **12**, and interconnect **16**. In the arrangement in FIG. **2**, however, die **5A** and **5B** are positioned side by side or horizontally, rather than stacked vertically with respect to each other.

Furthermore, the arrangement in FIG. **2** includes an interposer **18**. Interposer **18** is positioned below die **5A** and die **5B**. In other words, die **5A** and **5B** are positioned above interposer **18**, or stacked vertically with respect to interposer **18**. Interposer **18** couples to flexible interface blocks **10A-10B** via interconnect **12**. More specifically, interposer **18** may include a variety of coupling mechanisms that couple flexible interface block **10A** to flexible interface block **10B**. For example, as persons of ordinary skill in the art understand, the coupling mechanisms of interposer **18** may include one or more conductive traces **19A** and one or more TSVs **19B** to couple die **5A** and **5B** to one another (via flexible interface blocks **10A-10B**), to circuitry coupled to interposer **18** (via interconnects **16**), etc. As a result, inter-

poser **18** provides a path for electrical signals from flexible interface block **10A** to flexible interface block **10B**, from flexible interface block **10B** to flexible interface block **10A**, or both. Thus, via interposer **18**, flexible interface block **10A** and flexible interface block **10B** provide a mechanism for circuitry in die **5A** to communicate with circuitry in die **5B**.

The disclosed flexible interface blocks provide a mechanism for two or more die to communicate a desired number of information and power signals. FIG. **3** shows a circuit arrangement according to an exemplary embodiment for coupling together circuitry in semiconductor die by using one or more flexible interface blocks.

Specifically, die **5A** includes one or more flexible interface blocks **10A**. Similarly, die **5B** includes one or more flexible interface blocks **10B**. Flexible interface blocks **10A** couple to flexible interface blocks **10B** via interconnect **12**. In exemplary embodiments, flexible interface blocks **10** may have a desired number of data paths (as exemplified by interconnect **12**). By using one or more flexible interface blocks **10A** and **10B**, one may provide a desired number of information and power paths between semiconductor die **5A** and **5B**.

As an example, suppose that each of flexible interface blocks **10A** and **10B** includes **50** data/power paths (as exemplified by interconnect **12**, i.e., **50** coupling mechanisms in this example). Suppose further that one desires **200** data/power paths between die **5A** and die **5B**, one would include four flexible interface blocks **10A** in die **5A**, and four flexible interface blocks **10B** in die **5B**. Generally, the arrangement described can accommodate a variety of designs and specifications for the number of data/power paths between die **5A** and die **5B**, as persons of ordinary skill in the art understand. Thus, flexible interface blocks **10A-10B** provide a scalable and flexible mechanism for coupling a desired number of data/power lines in the circuitry of die **5A** to corresponding data/power lines to the circuitry in die **5B**.

FIG. **4** depicts a block diagram of a flexible interface block **10**, included in semiconductor die **5**, according to an exemplary embodiment. As described above, flexible interface block **10** includes a desired number of interconnect **12**. In the embodiment shown, flexible interface block **10** further includes buffer circuitry **20**, controller **22**, and routing interface **24**.

Interconnect **12**, as noted above, may include a variety of mechanisms or features. For example, in some embodiments, interconnect **12** may constitute microbumps. The microbumps may have a desired pitch or spacing, for example, **45** to **50** microns. Interconnect **12** may be unidirectional or bidirectional, i.e., provide communication in one direction or in both directions between semiconductor die. As noted above, the number and/or type of interconnect **12** depends on a number of factors related to a specific implementation or design, as persons of ordinary skill in the art understand. Examples of such factors include desired data bandwidth, desired number of data signals, desired number of power paths, etc.

As noted, interconnect **12** communicate a variety of signals between semiconductor die. Without limitation, interconnect **12** may communicate data, power, control signals, status signals between semiconductor die. By using desired types and numbers of signals, flexible and powerful interfaces may be accommodated between semiconductor die.

Buffer circuitry **20** couples to some (e.g., all data signals) or all (e.g., a mixture of data and power lines) interconnect **12**. Buffer circuitry **20** may provide one or more of the

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following functions in exemplary embodiments. First, buffer circuitry **20** may provide output buffer functionality by buffering, level-shifting (e.g., to accommodate differing voltage levels of the signal source and destination circuits), and/or conditioning signals from circuitry in die **5** in order to provide or transmit those signals to circuitry in another die (not shown). Second, buffer circuitry **20** may provide input buffer functionality by buffering, level-shifting (e.g., to accommodate differing voltage levels of the signal source and destination circuits), and/or conditioning signals from another die (not shown) in order to provide those signals to circuitry in die **5**. Furthermore, buffer circuitry **20** may provide bi-directional buffer functionality by buffering, level-shifting (e.g., to accommodate differing voltage levels of the signal source and destination circuits), and/or conditioning signals from circuitry in die **5** in order to provide or transmit those signals to circuitry in another die (not shown), and vice-versa.

In exemplary embodiments, buffer circuitry **20** may have various programmable or configurable features to provide flexibility. For example, in some embodiments, buffer circuitry **20** may have tristate functionality. As another example, buffer circuitry **20** may have fixed or programmable drive strength and/or slew rate.

Controller **22** couples to buffer circuitry **20**. Generally, controller **22** provides control and supervisory functions of flexible interface block **10**. For example, controller **22** may determine the timing, direction, and number of signals communicated between die. Thus, under the control of controller **22**, data/power signals are provided to buffer circuitry for ultimate communication to another semiconductor die.

Controller **22** may support one or more data or communication protocols. For example, suppose that a processor in one semiconductor die seeks to communicate with a memory in another semiconductor die. Suppose further that the memory uses a DDR protocol, well known to persons of ordinary skill in the art. Controller **22** may include circuitry to support communication between the processor and the memory according to the DDR protocol. Generally, controller **22** may support any desired protocol, for example, DDR, DDR2, DDR3, communication protocols, signaling protocols, etc.

Routing interface **24** couples to controller **22** and to circuitry (other than flexible interface block **10**) in die **5**. Specifically, routing interface **24** accepts data/power signals from circuitry (not shown explicitly) in die **5** and provides such signals to controller **22**. Conversely, routing interface **24** may receive data/power signals from controller **22** (e.g., as ultimately received from circuitry in another semiconductor die (not shown explicitly)), and provides such signals to circuitry (not shown explicitly) in die **5**.

FIG. **5** illustrates more details of a flexible interface block **10** according to an exemplary embodiment. In the embodiment shown, interconnect **12** includes a unidirectional output line (or link or interconnect) **12A**, a unidirectional input line **12B**, and a bidirectional line **12C**. Furthermore, interconnect **12** includes power line **12D** for supplying power to another device, and power line **12E** for receiving power from another device.

Buffer circuitry **20** includes an output buffer **20A**, which feeds output line **12A** of interconnect **12**. Buffer circuitry **20** also includes an input buffer **20B**, which is fed by input line **12B**. Furthermore, buffer circuitry **20** includes bidirectional buffer **20C**, which couples to line **12C** for transmitting or receiving signals. Note that buffer circuitry **20**, as shown, does not include circuitry for power lines **12D-12E**, and

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passes the power through buffer circuitry **20**. In other embodiments, however, buffer circuitry **20** may include circuitry for conditioning or regulating power, as desired.

In exemplary embodiments, controller **22** may include a variety of circuitry, ranging from hardened (fixed or non-programmable) to soft (fully programmable) or customizable circuitry. Thus, in some embodiments, controller **22** may include logic gates, registers, flip-flops, counters, finite state machines, hardened intellectual property (IP), memory, multiplexers (MUXs), latches, and the like. In some embodiments, controller **22** may include fully customizable or programmable logic, such as look-up tables (LUTs), soft IP, and generally circuitry similar to the programmable fabric of a programmable logic device (PLD). In yet other embodiments, controller **22** may include structured application specific IC (structured ASIC) circuitry. In such embodiments, with one or more mask changes, the functionality of controller **22** may be configured, customized, or programmed, as persons of ordinary skill in the art understand. Regardless of the exact implementation, in some embodiments, controller **22** in two or more flexible interface blocks **10** may be combined to provide additional flexibility, increased functionality, etc.

Generally speaking, routing interface **24** provides a mechanism for circuitry (not shown explicitly) in die **5** to communicate with controller **22** and, ultimately, with circuitry in another die (not shown explicitly). Routing interface **24** may include MUXs, buffers, registers, and similar circuitry. For example, in the embodiment shown, MUX **26** (under the control of controller **22**, for example) may select one of several signals received from circuitry (not shown explicitly) within die **5** (e.g., through link **34**), and provide the selected signal to controller **22**. As another example, MUX **28** (under the control of controller **22**, for example) may select one of several signals received from controller **22**, and provide the selected signal to circuitry (not shown explicitly) within die **5** (e.g., through link **34**).

Buffer or driver **30** may receive as an input a signal from routing interface **24** (e.g., a signal received via link **34** from circuitry (not shown explicitly) in die **5**), and provide an output signal to controller **22**. Conversely, buffer or driver **32** may receive as an input a signal from controller **22**, and provide an output signal to routing interface **24**. Routing interface **24** may provide the buffered signal to circuitry (not shown explicitly) in die **5** via link **34**.

In some embodiments, routing interface **24** may include circuitry similar to the programmable interconnect of a PLD. In such embodiments, the functionality of the circuitry in routing interface **24** may be programmed or configured, much in the same way as the routing fabric or resources of a PLD.

The embodiments described above include a variety of circuitry and functionality for flexible interface blocks **10**. In some embodiments, all of the features may be used. As persons of ordinary skill in the art understand, in some embodiments, one or more of the described features may be used. In other words, the circuitry and functionality included in one or more flexible interface blocks **10** depends on the specifications for a given design or implementation. Flexible interface blocks **10** can accommodate relatively simple to relatively complex interfacing specifications.

According to another aspect of the disclosure, flexible interface blocks **10** within a semiconductor die **5** may be grouped or arranged in a variety of ways. For example, in some embodiments, flexible interface blocks **10** within a semiconductor die **5** may be arranged as rows of flexible interface blocks. FIG. **6** shows such an arrangement. Spe-

cifically, die 5 includes a plurality of rows 36A-36C of flexible interface blocks 10. Rows 36A-36C may include one or more flexible interface blocks 10.

As another example, in some embodiments, flexible interface blocks 10 within a semiconductor die 5 may be arranged as columns of flexible interface blocks. FIG. 7 illustrates such an arrangement. Referring to FIG. 7, die 5 includes a plurality of columns 38A-38C of flexible interface blocks 10. Columns 38A-38C may include one or more flexible interface blocks 10.

In some embodiments, two or more flexible interface blocks 10 may be grouped together, for example, to provide additional data/power lines, wider data paths, more flexible or powerful controllers 22, etc. FIG. 8 depicts an example of such embodiments. Die 5 includes a plurality of flexible interface blocks 10. Flexible interface blocks 10 may be arranged in a number of ways, for example, in rows, in columns, individually positioned at desired locations, etc. Where two or more flexible interface blocks 10 neighbor each other or are positioned next to each other or relatively close to each other, they may be combined together to provide additional functionality or flexibility, as noted above. In the embodiment shown, four flexible interface blocks 10 are grouped together to form a group 40A of flexible interface blocks 10, and another four flexible interface blocks 10 are grouped together as group 40B of flexible interface blocks 10.

One may apply the disclosed concepts to a wide variety of ICs, including ICs that include fully or partially programmable or configurable circuitry. Thus, in some embodiments, a PLD integrated in one semiconductor die may include one or more flexible interface blocks 10 in order to couple to or interface to circuitry integrated in one or more additional semiconductor die. Note that in some embodiments, a PLD integrated in one semiconductor die may include one or more flexible interface blocks 10 in order to couple to or interface to one or more PLDs integrated in one or more additional semiconductor die

Without a loss of generality, the following paragraphs describe the application of disclosed concepts to PLDs. FIG. 9 depicts a general block diagram of a PLD 103 according to an exemplary embodiment that includes one or more flexible interface blocks 10. PLD 103 may be included or fabricated in a semiconductor die, such as those described above and shown in FIGS. 1-8.

Referring to FIG. 9, PLD 103 includes configuration circuitry 130, configuration memory (CRAM) 133, control circuitry 136, programmable logic 106, programmable interconnect 109, and I/O circuitry 112. In addition, PLD 103 may include test/debug circuitry 115, one or more processors 118, one or more communication circuitry 121, one or more memories 124, one or more controllers 127, one or more flexible interface blocks 10, and initialization circuit 139, as desired.

Note that PLD 103 may include other blocks and circuitry, as persons of ordinary skill in the art understand. Examples of such circuitry include clock generation and distribution circuits, redundancy circuits, and the like. Furthermore, PLD 103 may include analog circuitry, other digital circuitry, and/or mixed-signal circuitry, as desired.

Programmable logic 106 includes blocks of configurable or programmable logic circuitry, such as LUTs, product-term logic, MUXs, logic gates, registers, memory, and the like. Programmable interconnect 109 couples to programmable logic 106 and provides configurable interconnects (coupling mechanisms) between various blocks within programmable logic 106 and other circuitry within or outside

PLD 103. Programmable interconnect 109 may include MUXs, pass transistors, buffers, and the like, as persons of ordinary skill in the art understand.

Control circuitry 136 controls various operations within PLD 103. Under the supervision of control circuitry 136, PLD configuration circuitry 130 uses configuration data (which it may obtain from an external source, such as a storage device, a host, etc.) to program or configure the functionality of PLD 103. Configuration data are typically stored in CRAM 133. The contents of CRAM 133 determine the functionality of various blocks of PLD 103, such as programmable logic 106 and programmable interconnect 109. Initialization circuit 139 may cause the performance of various functions at reset or power-up of PLD 103.

I/O circuitry 112 may constitute a wide variety of I/O devices or circuits, as persons of ordinary skill in the art who have the benefit of the disclosure understand. I/O circuitry 112 may couple to various parts of PLD 103, for example, programmable logic 106 and programmable interconnect 109. I/O circuitry 112 provides a mechanism and circuitry for various blocks within PLD 103 to communicate with external circuitry or devices.

Test/debug circuitry 115 facilitates the testing and troubleshooting of various blocks and circuits within PLD 103. Test/debug circuitry 115 may include a variety of blocks or circuits known to persons of ordinary skill in the art who have the benefit of the disclosure. For example, test/debug circuitry 115 may include circuits for performing tests after PLD 103 powers up or resets, as desired. Test/debug circuitry 115 may also include coding and parity circuits, as desired.

PLD 103 may include one or more processors 118. Processor 118 may couple to other blocks and circuits within PLD 103. Processor 118 may receive data and information from circuits within or external to PLD 103 and process the information in a wide variety of ways, as persons skilled in the art with the benefit of the disclosure in this document appreciate. One or more of processor(s) 118 may constitute a digital signal processor (DSP). DSPs allow performing a wide variety of signal processing tasks, such as compression, decompression, audio processing, video processing, filtering, and the like, as desired.

PLD 103 may also include one or more communication circuits 121. Communication circuit(s) 121 may facilitate data and information exchange between various circuits within PLD 103 and circuits external to PLD 103, as persons of ordinary skill in the art understand. For example, in some embodiments, communication circuitry 121 may include transceivers for communicating with other electronic devices.

PLD 103 may further include one or more memories 124 and one or more memory controller(s) 127. Memory 124 allows the storage of various data and information (such as user-data, intermediate results, calculation results, etc.) within PLD 103. Memory 124 may have a granular or block form, as desired. Memory controller 127 allows interfacing to, and controlling the operation and various functions of memory 124 and/or memory external to PLD 103 and/or die 5 (e.g., memory integrated in another semiconductor die (not shown)). For example, controller 127 may constitute a memory controller that interfaces to and controls an external (e.g., memory integrated in another semiconductor die (not shown)) synchronous dynamic random access memory (SDRAM), as desired.

Flexible interface blocks 10 may include the circuitry, and provide the functionality, described above. Flexible interface blocks 10 couple to programmable interconnect 109.

Programmable interconnect **109** may in turn couple to one or more blocks of circuitry in PLD **103**, such as the blocks shown in the figure. Such blocks may communicate with flexible interface blocks **10** via programmable interconnect **109**. Furthermore, flexible interface blocks **10** may communicate with circuitry within another semiconductor die (not shown) via interconnect **12**.

FIG. **10** shows a block diagram of a PLD **103** that includes programmable resources and flexible interface blocks according to an exemplary embodiment. More specifically, the figure shows a floor-plan of a PLD that **103** includes programmable logic **106** arranged as a two-dimensional array. Programmable interconnect **109**, arranged as horizontal interconnect and vertical interconnect, couples the blocks of programmable logic **106** to one another.

PLD **103** includes flexible interface blocks **10**, which may be arranged as a row, a column, or in a two-dimensional or array pattern. Flexible interface blocks **10** couple to one or more blocks in PLD **103** via programmable interconnect **109**. As noted above, two or more flexible interface blocks **10** may be grouped together to provide increased bandwidth, throughput, functionality, etc. Such groups of flexible interface blocks may couple to programmable logic **106** or other blocks of circuitry in PLD **103** (see, e.g., FIG. **9**) via programmable interconnect.

One may place the various blocks in FIG. **10** a particular manner so as to implement a user's design, as persons of ordinary skill in the art understand. A block, part of a block, or a set of blocks may constitute a tile or region of PLD **103**. PLD **103** may thus include a number of tiles, arranged in a desired configuration (e.g., as two halves, four quadrants, etc.), as persons of ordinary skill in the art understand. In other embodiments, PLD **103** may include rows and/or columns of circuitry or blocks of circuitry.

Flexible interface blocks **10** may advantageously be used at a more granular level in PLDs. Specifically, in some embodiments, the core or fabric of PLD **103** may include a more granular structure of programmable circuitry (e.g., programmable logic, programmable interconnect, etc.). Flexible interface blocks **10** may be used in such embodiments to provide a flexible, customizable interface at a desired level of granularity in PLD **103**.

FIG. **11** shows a circuit arrangement of blocks of programmable logic **106** coupled to flexible interface blocks **10** via programmable interconnect **109** according to an exemplary embodiment. In the exemplary embodiment shown, programmable logic **106** includes logic elements or programmable logic elements, circuits, or blocks **150**, local interconnect **152**, interface circuit **153**, and interface circuit **156**. Flexible interface blocks may couple to programmable logic **106** at a lower level than the global PLD resource level, at the global PLD resource level, or both.

Logic elements **150** provide configurable or programmable logic functions, for example, LUTs, flip-flops, registers, product-term logic, etc., as persons of ordinary skill in the art understand. Local interconnect **152** provides a configurable or programmable mechanism for logic elements **150** to couple to one another. In addition, local interconnect **152** provides a configurable or programmable mechanism for logic elements **150** to one or more flexible interface blocks **10**.

Logic elements **150** may couple to one another, to one or more flexible interface blocks **10**, or to programmable interconnect **109** (sometimes called "global interconnect"), as desired. Interface circuit **156** and interface circuit **153** provide a configurable or programmable way for program-

mable logic **106** block of circuitry to couple to programmable interconnect **109** (and hence to other programmable logic **106**).

Interface circuit **156** and interface circuit **153** may include MUXs, DEMUXs, registers, buffers, pass gates, drivers, and the like, as persons of ordinary skill in the art understand. At a higher level, one may combine a number of logic elements **150** and associated circuitry to realize a larger programmable block. One may repeat this process as desired or appropriate in a given situation to generate programmable blocks of circuitry with a desired level of granularity of programmability. At one or more of such levels, the hierarchical structure or fabric or circuitry of PLD **103** may be coupled to one or more flexible interface blocks **10**, which may be arranged in a number of ways (e.g., as individual blocks, rows, columns, two-dimensional arrays).

Once a desired number of flexible interface blocks **10** have been included in a PLD **103**, the programmable nature of the PLD, together with flexible interface blocks **10**, provides the user with a scalable, flexible architecture for realizing or implementing a wide variety of electronic circuitry or systems with desired functionality. To aid the user in implementing or realizing such circuitry or systems, one may use a computer-aided design (CAD) flow or software.

FIG. **12** illustrates various software modules that PLD CAD software or flow according to an exemplary embodiment uses. The modules include design-entry module **203**, synthesis module **206**, place-and-route module **209**, and verification module **212**. The CAD flow may have a variety of applications and provide various functionality. Examples include design area optimization or planning, placement, timing performance and closure, power planning, routability optimization or planning, etc.

Design-entry module **203** allows the editing of various design description files using graphical or textual descriptions of a circuit or its behavior, such as schematics, hardware description languages (HDL), or waveforms, as desired. The user may generate the design files by using design-entry module **203** or by using a variety of electronic design automation (EDA) or CAD tools (such as industry-standard EDA tools), as desired. The user may enter the design in a graphic format, a waveform-based format, a schematic format, in a text or binary format, or as a combination of those formats, as desired.

The user may specify one or more flexible interface block **10** as part of the specification of the overall PLD. By using flexible interface blocks **10**, the user's circuit may couple to other circuitry integrated in one or more semiconductor die, as described above. The user may provide a variety of specifications for flexible interface block **10**. Examples include location (placement specifications), power specifications, timing specifications, functionality, etc. The user may also group two or more flexible interface blocks **10**, as described above.

In some embodiments, the CAD flow may logically treat flexible interface blocks **10** and the circuitry to which they couple as blocks of circuitry or IP of PLD **103**. Thus, although such flexible interface blocks **10** may physically interface to circuitry integrated in a different die than that of PLD **103**, for the purpose of analyzing, synthesizing, and placing the user's circuit, the CAD flow may consider such circuitry as being a part of the circuitry of PLD **103**, and located at the location(s) of flexible interface block(s) **10**. In other words, flexible interface blocks **10** and associated circuitry (e.g., a memory block integrated in a different die than that of PLD **103**) may be represented or treated as an

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embedded memory block in PLD **103**. Thus, in this example, the memory block may be represented or modeled (e.g., logically) as flexible interface blocks **10** coupled to the memory block.

By using a more abstract object, for example, a macro, the various physical, electrical, and logical attributes of flexible interface block(s) **10** and the circuitry external to PLD **103** (e.g., integrated in a different die than the die of PLD **103**) may be attributed to the abstract object. In this manner, a 3D structure (e.g., one die stacked above another die, either or both of which may be a PLD) may be represented to the user as a two-dimensional (2D) structure. Thus, the CAD flow will handle the complexities associated with the physical structure, with the logical structure, the electrical structure, etc. (timing, electrical interface, voltage levels, and the like). As a result, the complexities associated with the 3D structure may be hidden or made transparent to the user of the PLD (or PLD CAD) by representing the 3D structure as a 2D structure. As persons of ordinary skill in the art understand, this concept is not limited to memory blocks, and may be applied to a wide variety of circuitry and IP blocks, as desired.

For example, suppose that the user wants to use a memory block to implement his or her circuit. The CAD flow may include representations of the memory block that specify the memory block as integrated in a different die than the die of PLD **103**, where the die that includes the memory block couples to PLD **103** via one or more flexible interface blocks **10**, at location X in the floorplan of PLD **103**. From the perspective of the user, the memory block is a macro that he or she may use as part of the design specifications. The PLD CAD flow, using the location specifications, and electrical (timing, signals, controller design, protocol, etc.), physical (e.g., different die), and logical attributes (width, depth, etc.) of the memory block, properly represents the memory block in the user's design.

Synthesis module **206** accepts the output of design-entry module **203**. Based on the user-provided design, synthesis module **206** generates appropriate logic circuitry that realizes the user-provided design. One or more PLDs (not shown explicitly), such as PLD **103** in FIG. **1**, implement the synthesized overall design or system.

Synthesis module **206** may also generate any glue logic that allows integration and proper operation and interfacing of various modules in the user's designs. For example, synthesis module **206** provides appropriate hardware so that an output of one block properly interfaces with an input of another block. Synthesis module **206** may provide appropriate hardware so as to meet the specifications of each of the modules in the overall design or system. If the user's design includes abstract objects or circuitry or components, such as circuitry coupled to PLD **103** via flexible interface block(s) **10**, the synthesis module represents the object in the user's design using the attributes of the object.

Furthermore, synthesis module **206** may include algorithms and routines for optimizing the synthesized design. Through optimization, synthesis module **206** seeks to more efficiently use the resources of the one or more PLDs that implement the overall design or system. Synthesis module **206** provides its output to place-and-route module **209**. Following synthesis, one may include a technology mapping module (not shown explicitly).

Place-and-route module **209** uses the designer's timing specifications to perform optimal logic mapping and placement in the floorplan of PLD **103**. The logic mapping and placement determine the use of logic resources within the PLD(s). By the use of particular programmable intercon-

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nects with the PLD(s) for certain parts of the design, place-and-route module **209** helps optimize the performance of the overall design or system. By the proper use of PLD routing resources, place-and-route module **209** helps to meet the critical timing paths of the overall design or system. As noted above, flexible interface block(s) **10** may have predetermined, pre-assigned, reserved, or allocated locations in the floorplan of PLD **103**. Place-and-route module **209** uses information about such locations to properly route other components or circuitry to flexible interface block(s) **10** and, hence, to other circuitry integrated in different die than the die of PLD **103**.

Place-and-route module **209** optimizes the critical timing paths to help provide timing closure faster, as persons of ordinary skill in the art understand. As a result, the overall design or system can achieve faster performance (i.e., operate at a higher clock rate or have higher throughput).

Verification module **212** performs simulation and verification of the design. The simulation and verification seek in part to verify that the design complies with the user's prescribed specifications. The simulation and verification also aim at detecting and correcting any design problems before prototyping the design. Thus, verification module **212** helps the user to reduce the overall cost and time-to-market of the overall design or system.

Verification module **212** may support and perform a variety of verification and simulation options, as desired. The options may include functional verification, test-bench generation, static timing analysis, timing simulation, hardware/software simulation, in-system verification, board-level timing analysis, signal integrity analysis and electromagnetic compatibility (EMC), formal netlist verification, and the like, as persons of ordinary skill in the art who have the benefit of the description of this disclosure understand.

Note that one may perform other or additional verification techniques as desired and as persons of ordinary skill in the art who have the benefit of this disclosure understand. Verification of the design may also be performed at other phases in the flow, as appropriate, and as desired.

As noted above, although the above description relates in part the application of the disclosed concepts to PLDs, one may apply the disclosed concepts to a variety of other electronic circuits and devices, by making modifications that fall within the knowledge of persons of ordinary skill in the art. Some examples of such devices include custom, standard-cell, gate-array, field-programmable gate arrays (FPGAs), complex PLDs (CPLDs), and structured ASIC implementations.

One may run or execute the disclosed algorithms, methods, software (e.g., CAD software), or firmware (e.g., where part of the functionality of some circuitry, such as body bias control circuitry, is implemented using firmware) on computer systems or processors. Specifically, the PLD CAD flow may be implemented as software that runs on an information processing system or computer, such as the information processing system shown in FIG. **13**. Persons of ordinary skill in the art understand that one may use a wide variety of other information processing apparatus, computer systems, processors, microcomputers, workstations, and the like, as desired. Thus, FIG. **13** illustrates merely one example.

System **1000** includes a computer device **1005**, an input device **1010**, a video/display device **1015**, and a storage/output device **1020**, although one may include more than one of each of those devices, as desired. Computer device **1005** couples to input device **1010**, video/display device **1015**, and storage/output device **1020**. System **1000** may

include more than one computer device **1005**, for example, a set of associated computer devices or systems, as desired, and as persons of ordinary skill in the art understand.

System **1000** operates in association with input from a user. The user input typically causes system **1000** to perform specific desired information-processing tasks, including circuit simulation. System **1000** in part uses computer device **1005** to perform those tasks. Computer device **1005** includes an information-processing circuitry, such as a central-processing unit (CPU), although one may use more than one CPU or information-processing circuitry, as persons skilled in the art would understand.

Input device **1010** receives input from the user and makes that input available to computer device **1005** for processing. The user input may include data, instructions, or both, as desired. Input device **1010** may constitute an alphanumeric input device (e.g., a keyboard), a pointing device (e.g., a mouse, roller-ball, light pen, touch-sensitive apparatus, for example, a touch-sensitive display, or tablet), or both. The user operates the alphanumeric keyboard to provide text, such as ASCII characters, to computer device **1005**. Similarly, the user operates the pointing device to provide cursor position or control information to computer device **1005**.

Video/display device **1015** displays visual images or graphics to the user. The visual images may include information about the operation of computer device **1005**, such as graphs, pictures, images, and text. The video/display device may constitute a computer monitor or display, a projection device, and the like, as persons of ordinary skill in the art would understand. If a system uses a touch-sensitive display or touchscreen, the display may also operate to provide user input to computer device **1005**.

Storage/output device **1020** allows computer device **1005** to store information for additional processing or later retrieval (e.g., softcopy), to present information in various forms (e.g., hardcopy), or both. As an example, storage/output device **1020** may constitute a magnetic, optical, or magneto-optical drive capable of storing information on a desired medium and in a desired format. As another example, storage/output device **1020** may constitute a printer, plotter, or other output device to generate printed or plotted expressions of the information from the computer device **1005**.

Computer-readable medium **1025** interrelates structurally and functionally to computer device **1005**. Computer-readable medium **1025** stores, encodes, records, and/or embodies functional descriptive material. By way of illustration, the functional descriptive material may include computer programs, computer code, computer applications, and/or information structures (e.g., data structures or file systems). When stored, encoded, recorded, and/or embodied by computer-readable medium **1025**, the functional descriptive material imparts functionality. The functional descriptive material interrelates to computer-readable medium **1025**.

Information structures within the functional descriptive material define structural and functional interrelations between the information structures and computer-readable medium **1025** and/or other aspects of system **1000**. These interrelations permit the realization of the information structures' functionality. Moreover, within such functional descriptive material, computer programs define structural and functional interrelations between the computer programs and computer-readable medium **1025** and other aspects of system **1000**. These interrelations permit the realization of the computer programs' functionality.

By way of illustration, computer device **1005** reads, accesses, or copies functional descriptive material into a

computer memory (not shown explicitly in the figure) of computer device **1005**. Computer device **1005** performs operations in response to the material present in the computer memory. Computer device **1005** may perform the operations of processing a computer application that causes computer device **1005** to perform additional operations. Accordingly, the functional descriptive material exhibits a functional interrelation with the way computer device **1005** executes processes and performs operations.

Furthermore, computer-readable medium **1025** constitutes an apparatus from which computer device **1005** may access computer information, programs, code, and/or applications. Computer device **1005** may process the information, programs, code, and/or applications that cause computer device **1005** to perform additional operations.

Note that one may implement computer-readable medium **1025** in a variety of ways, as persons of ordinary skill in the art would understand. For example, memory within computer device **1005** may constitute a computer-readable medium **1025**, as desired. Alternatively, computer-readable medium **1025** may include a set of associated, interrelated, coupled (e.g., through conductors, fibers, etc.), or networked computer-readable media, for example, when computer device **1005** receives the functional descriptive material from a network of computer devices or information-processing systems. Note that computer device **1005** may receive the functional descriptive material from computer-readable medium **1025**, the network, or both, as desired.

Referring to the figures, persons of ordinary skill in the art will note that the various blocks shown might depict mainly the conceptual functions and signal flow. The actual circuit implementation might or might not contain separately identifiable hardware for the various functional blocks and might or might not use the particular circuitry shown. For example, one may combine the functionality of various blocks into one circuit block, as desired. Furthermore, one may realize the functionality of a single block in several circuit blocks, as desired. The choice of circuit implementation depends on various factors, such as particular design and performance specifications for a given implementation. Other modifications and alternative embodiments in addition to those described here will be apparent to persons of ordinary skill in the art. Accordingly, this description teaches those skilled in the art the manner of carrying out the disclosed concepts, and is to be construed as illustrative only.

The forms and embodiments shown and described should be taken as illustrative embodiments. Persons skilled in the art may make various changes in the shape, size and arrangement of parts without departing from the scope of the disclosed concepts in this document. For example, persons skilled in the art may substitute equivalent elements for the elements illustrated and described here. Moreover, persons skilled in the art may use certain features of the disclosed concepts independently of the use of other features, without departing from the scope of the disclosed concepts.

The invention claimed is:

1. An interface circuit comprising:  
buffer circuitry;

routing circuitry coupled to circuitry external to the interface circuit, wherein a programmable interconnect couples the routing circuitry to the circuitry external to the interface circuit; and  
control circuitry coupled between the buffer circuitry and the routing circuitry.

2. The interface circuit defined in claim 1, wherein the interface circuit is reconfigurable.

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3. The interface circuit defined in claim 1, wherein the interface circuit is formed on an integrated circuit die and the buffer circuitry is coupled to additional circuitry external to the integrated circuit die.

4. The interface circuit defined in claim 1, wherein the interface circuit is formed on an integrated circuit die and the circuitry external to the interface circuit is within the integrated circuit die.

5. The interface circuit defined in claim 1, wherein the routing circuitry comprises a multiplexer that includes an output terminal coupled to the control circuitry.

6. The interface circuit defined in claim 1, wherein the routing circuitry comprises a multiplexer that includes an input terminal coupled to the control circuitry.

7. The interface circuit defined in claim 1, wherein the routing circuitry includes an input terminal, wherein the buffer circuitry includes an output terminal, and wherein the control circuitry couples the input terminal of the routing circuitry to the output terminal of the buffer circuitry.

8. The interface circuit defined in claim 7, wherein the routing circuitry further includes an output terminal, wherein the buffer circuitry further includes an input terminal, and wherein the control circuitry further couples the input terminal of the buffer circuitry to the output terminal of the routing circuitry.

9. The interface circuit defined in claim 1, wherein the buffer circuitry comprises a bidirectional buffer.

10. The interface circuit defined in claim 1, wherein a portion of the interface circuit is formed at least partly from programmable circuitry on an integrated circuit die.

11. The interface circuit defined in claim 10, wherein the programmable circuitry includes the programmable interconnect and programmable logic coupled to the interface circuit via the programmable interconnect.

12. The interface circuit defined in claim 1, wherein the circuitry external to the interface circuit comprises programmable logic on an integrated circuit.

13. A customizable interface circuit in a first semiconductor die, comprising:

- a routing interface coupled to a first circuit in the first semiconductor die;
- interconnect circuitry coupled to a second semiconductor die; and
- control circuitry coupled between the routing interface and the interconnect circuitry, wherein the first circuit

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is coupled to the second semiconductor die via the routing interface, the control circuitry, and the interconnect circuitry.

14. The customizable interface circuit defined in claim 13, wherein the second semiconductor die is disposed above the first semiconductor die.

15. The customizable interface circuit defined in claim 13, wherein the first and second semiconductor dies are mounted on an interposer.

16. The customizable interface circuit defined in claim 13, wherein the first semiconductor die comprises programmable circuitry and wherein the customizable interface circuit is part of the programmable circuitry.

17. A method of using a flexible interface block in an integrated circuit die, the method comprising:

- configuring the flexible interface block to receive input signals from an additional integrated circuit die;
- receiving the input signals at buffer circuitry in the flexible interface block;
- generating corresponding output signals at the buffer circuitry in the flexible interface block; and
- with a routing interface circuit in the flexible interface block, providing the corresponding output signals to logic circuitry within the integrated circuit die and external to the flexible interface block.

18. The method defined in claim 17, wherein configuring the flexible interface block comprises implementing a number of signal paths between the flexible interface block and the additional integrated circuit die based on the input signals.

19. The method defined in claim 17, wherein the additional integrated circuit die is configured to operate according to a protocol and wherein configuring the flexible interface block comprises configuring a controller coupled between the buffer and the routing interface circuit to communicate with the additional integrated circuit die using the protocol.

20. The method defined in claim 17, further comprising: with a controller coupled between the buffer and the routing interface circuit, routing the corresponding output signals from the buffer circuitry to the routing interface circuit.

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